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Supplementation of extruded foams with wheat bran: Effect on textural properties

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Abstract

The objective of this study was to investigate the effect of wheat bran concentrations on the mechanical properties determining the texture of extruded carbohydrate matrices. For this wheat flour was extruded under different conditions with an increasing concentration of wheat bran. The mechanical properties were assessed using a three-point bending test and the cellular structure was determined by micro-computed X-ray tomography. Regardless of the bran concentration, the stress at rupture of the extruded foams was positively correlated with their relative density according to the Gibson-Ashby model. At same relative densities and bran concentration, finer structures with higher density of small cells led to a higher mechanical strength of the foams. Expanded foams with added bran at an intermediate level showed increased mechanical strength. This was attributed to the finer cellular structures obtained. The effect of increasing the bran to a higher concentration on the mechanical properties was depending on the cell wall thickness and bran particle dimensions.

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Keywords: extrusion; wheat bran; fibres; mechanical properties; glass transition

1. Introduction

The effect of dietary fibers on the mechanical properties of extruded foams was reported in a limited number of studies. The effect was found to be fiber type- and concentration-dependant. While soluble fibers, such as pectin, appeared to decrease the breaking force, insoluble fibers such as wheat fibers had an opposite effect [1, 2]. The higher force necessary to rupture extruded starchy-matrices containing wheat fibers was associated to their reduced bulk expansion [1, 2]. The mechanical properties of solid foams are

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mainly driven by their bulk dimensions, porosity and shape. Nevertheless, at similar bulk properties (i.e. shape, dimensions and porosity), the mechanical properties may also be modulated by the distribution of the continuous (cell walls) and dispersed (air) phases [3, 4]. Changing the microstructure of extruded foams may allow improving their texture while maintaining similar bulk properties such as dimensions and density. Little has been reported in the literature on the effect of wheat bran on the mechanical properties of extruded foams and the correlation to the cellular and cell wall material properties of such matrices. Understanding this link will enable to generate structures that are delivering an optimal texture for wheat bran-containing products. For this, in this study the relationship between the expansion properties, cellular structure and mechanical properties of extruded foams supplemented with wheat bran was assessed. This was performed by measuring the mechanical properties using a three-point bending test, determining the bulk dimensions, assessing the cellular structure by X-ray tomography and investigating the phases distribution in the cell walls by light microscopy.

Nomenclature

σ	Stress at rupture
ρ	Density
*	Extrudate
D	Relative density
D_s	Die diameter
F	Breaking force
L	Sample length
L_s	Die length
LB	Low bran concentration
MCS	Mean cell size
MCWT	Mean cell wall thickness
MC	Moisture content
HB	High bran concentration
r_e	Sample radius
RF	Refined flour
s	Material

2. Material and Methods

2.1 Materials

Wheat flour type 550 and wheat bran were obtained from Provimi Kliba S.A. (Cossonay, Switzerland). Wheat bran (51.4 % fibers) was added to refined wheat flour (coded RF) (2.8 % fibers) to achieve two fiber levels: 12.6 % (coded LB for low bran concentration) and 24.4 % (coded HB for high bran concentration) (quantified using the AOAC 985.29 method). Two qualities of wheat bran were used: a "fine" (Table 1) bran with an average volume weighted diameter of 224 μm ± 6 μm and a "coarse" (Table

1) bran with an average volume weighted particle size of 317 μm ± 1 μm. The particle size was measured in medium-chain triglyceride oil by laser diffraction (Mastersizer 2000, Malvern, Herrenberg, Germany). Cooking-extrusion was performed using an Evolum 25 twin-screw extruder (Clextral, Firminy, France) with a screw diameter D_s of 25 mm and a barrel length L_s of 400 mm (L_s/D_s = 16). Eight experimental conditions (hereafter numbered from 1 to 8) were used varying the extruded screw speed, water content in the feed material and barrel temperature according to the experimental procedure shown in Table 1. A circular die of 10 mm length and 3.2 mm diameter was used. After extrusion, the samples were collected and dried in an oven at 60 °C for 16 hours.

Table 1: Process conditions, cellular structure and mechanical properties (RF: refined flour, LB: low bran concentration, HB: high bran concentration) (D: relative density, MCWT: mean cell wall thickness, MCS: mean cell size, σ^*: stress at rupture, NA: not applicable)

	Barrel Temp. [°C]	Feed water [%]	Screw speed [rpm]	Bran particle size [-]	Fiber content [%]	D [-]	MCWT [μm]	Cell density [cm^{-3}]	MCS [μm]	σ^* [MPa]
RF1	120	18	400	NA	NA	0.066 ± 0.008	70	100	1610	0.58 ± 0.13
RF2	120	18	800	NA	NA	0.038 ± 0.002	45	430	3650	0.27 ± 0.08
RF3	120	22	400	NA	NA	0.150 ± 0.010	265	2	3220	0.82 ± 0.20
RF4	120	22	800	NA	NA	0.044 ± 0.001	85	30	1900	0.37 ± 0.08
RF5	180	18	400	NA	NA	0.043 ± 0.003	45	320	2180	0.32 ± 0.07
RF6	180	18	800	NA	NA	0.029 ± 0.003	30	620	1850	0.19 ± 0.04
RF7	180	22	400	NA	NA	0.076 ± 0.007	75	50	1730	0.67 ± 0.14
RF8	180	22	800	NA	NA	0.041 ± 0.002	30	740	1940	0.86 ± 0.19
LB1	120	18	400	Fine	12.6	0.089 ± 0.002	50	510	1140	0.87 ± 0.15
LB2	120	18	800	Coarse	12.6	0.066 ± 0.002	30	800	540	0.47 ± 0.09
LB3	120	22	400	Coarse	12.6	0.183 ± 0.007	110	120	820	1.80 ± 0.37
LB4	120	22	800	Fine	12.6	0.086 ± 0.003	55	220	890	0.99 ± 0.15
LB5	180	18	400	Coarse	12.6	0.061 ± 0.004	30	1250	590	0.71 ± 0.16
LB6	180	18	800	Fine	12.6	0.042 ± 0.001	25	3120	470	0.44 ± 0.10
LB7	180	22	400	Fine	12.6	0.089 ± 0.010	40	380	850	1.33 ± 0.31
LB8	180	22	800	Coarse	12.6	0.065 ± 0.005	25	2120	410	1.15 ± 0.18
HB1	120	18	400	Coarse	24.4	0.121 ± 0.006	40	1610	380	1.00 ± 0.12
HB2	120	18	800	Fine	24.4	0.084 ± 0.007	30	3650	210	0.55 ± 0.17
HB3	120	22	400	Fine	24.4	0.202 ± 0.014	90	170	580	2.93 ± 0.45
HB4	120	22	800	Coarse	24.4	0.119 ± 0.009	40	860	400	1.33 ± 0.15
HB5	180	18	400	Fine	24.4	0.114 ± 0.019	25	1260	270	0.68 ± 0.16
HB6	180	18	800	Coarse	24.4	0.105 ± 0.011	25	4980	230	0.50 ± 0.14
HB7	180	22	400	Coarse	24.4	0.117 ± 0.010	35	1710	280	1.48 ± 0.26
HB8	180	22	800	Fine	24.4	0.111 ± 0.011	30	2830	230	1.10 ± 0.27

2.2. Samples structure characterization

2.2.1. Sample relative density

The determination of the relative density *D* was performed according to equation (1):

$$D = \frac{\rho^* \left(1 - \mathrm{MC}^*\right)}{\rho_s \left(1 - \mathrm{MC}_s\right)} \quad (1)$$

where ρ and MC are the density and the moisture content (wet basis) and indices (*) and (*s*) refer to the extrudate and material, respectively. The raw material density, used to estimate the melt density and the cell wall material density ρ_s was measured by helium pycnometry (10 replicates, Accupyc 1330, Micrometrics, Verneuil en Halatte, France). The extrudate bulk density ρ^* was determined by beads displacement (three repetitions on five pieces).

2.2.2. Cellular structure determination

The samples were scanned using a high resolution desktop cone beam X-ray micro-computed tomography system (Scanco μCT 35, Scanco Medical AG, Brütisellen, Switzerland). It consists of a micro-focused sealed X-ray tube operating at a voltage of 55 kV and a current of 145 μA. X-ray shadow images were acquired every 0.18° through a 360° rotation. The reconstruction of the image used a Shepp & Logan filtered back-projection extended to a cone-beam geometry. A voxel size of 6 μm was selected in order to capture the thin cell walls while scanning statistically a significant part of each sample. 3D image analyses were generated using OpenVMS (v.8.3, Hewlett-Packard). A volume of interest (VOI) was selected, segmented and the porosity of the pellet calculated as the ratio of the volume of the cells to the entire VOI. The cell size and cell wall thickness distributions were calculated using the method developed by Hildebrand & Rüegsegger [5]. The density of unconnected cells was calculated using a component labeling operation. Only the cells larger than the average cell wall thickness were taken into account in the calculation of the cell density to exclude voids comprising only a few voxels and originating from measurement noise.

2.3. Light microscopy

Extruded samples were embedded in the resin Technovit 7100 (Kulzer-technik A.G., Wehrheim, Germany). Slices of 5 μm in the longitudinal direction (parallel to the direction of extrusion) were taken using a microtome equipped with a tungsten knife (2055, Leica Geosystems, AG, Heerbrugg, Switzerland). Starch was stained with a 1 % Lugol solution (L6146, Sigma-Aldrich A.G., Buchs, Switzerland), and proteins with a Light green solution (Fluka 62110, Sigma-Aldrich A.G., Buchs, Switzerland). The slices were investigated using a light microscope (Zeiss Axioplan, Carl Zeiss A.G., Feldbach, Switzerland) equipped with a color camera (Axicam MRc5 camera, Zeiss Axioplan Carl Zeiss A.G., Feldbach, Switzerland).

2.4. Mechanical properties

The mechanical properties of extruded foams were measured using a three-point bending test performed on a texture analyzer (TA-HDi, Stable Microsystems, Godalming, UK) equipped with a 50 kg load cell and applying a crosshead speed of 1 mm s^{-1}. The samples were equilibrated prior to testing at a water activity of 0.30 in humidity cabinets (C+ 10/60, CTS A.G., Germany). The rupture stress σ^* of the

extruded samples was derived from the maximum force at rupture F. It was calculated according to equation (2):

$$\sigma^* = \frac{FL}{\pi r_e^3} \tag{2}$$

with r_e the sample average radius and L, the distance between the supports (L = 50 mm). The relationship between the relative density ($D = \rho^*/\rho_s$) and the stress at rupture was modeled according to equation (3) (Gibson-Ashby model [6]):

$$\frac{\sigma^*}{\sigma_s} \propto \left(\frac{\rho^*}{\rho_s}\right)^n \tag{3}$$

The power law index n was obtained by fitting of the experimental points.

3. Results & discussion

3.1. Application of the Gibson-Ashby model

Stress-strain curves obtained after compression of the extruded refined flour with increasing bran concentration showed a linear increase in stress at low strain and a fracture at higher strain. Such stress/strain curves are typical for elastic brittle foams [6].

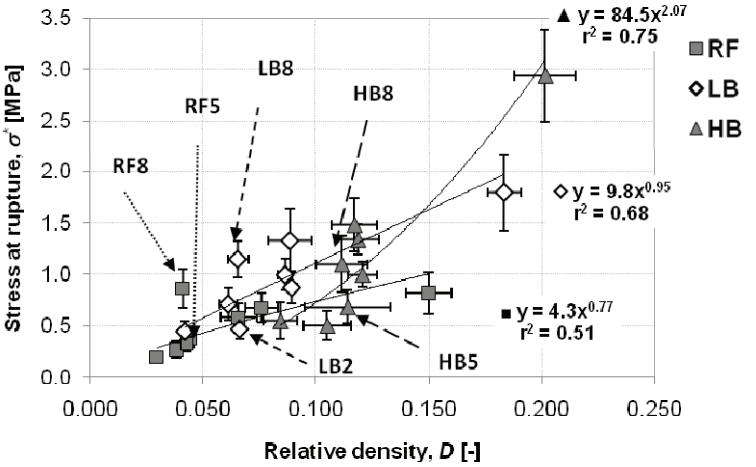

Fig. 1: Stress at rupture σ^* vs. relative density D of samples with increasing bran concentration extruded at different conditions (■ refined flour (RF), ◊ low bran concentration (LB) and ▲ high bran concentration (HB))

The stress at rupture of the extruded foams increased with their relative density (see Fig. 1). The relative densities obtained in this work were within the range where the analogy to solid foams can be made (usually valid for $D < 0.030$) [6]. The Gibson-Ashby model is linking the mechanical properties of

solid foams to their relative density according to a power law relationship (equation 3). It was applied to the measured values of stress at rupture according to the bran concentration (see Fig. 1). The correlation factor r^2 between the experimental values of stress at rupture and the power law fitting of these values according to the Gibson-Ashby model was not satisfying (Fig. 1). It was nevertheless improved when increasing the bran concentration with respectively r^2 = 0.51, 0.68 and 0.75 for the refined flour (RF) and bran-containing samples (LB and HB) (Fig. 2a). A similar power law index n was found for the refined flour (RF) and low bran (LB) samples (n = 0.77 and 0.97), while at higher bran concentration (HB) a higher power law index was reported (n = 2.07) (Fig. 1). The power law index n for the refined flour (RF) and low bran (LB) samples was closer to the theoretical value obtained for open cell structures (n = 1.5) [6]. The power law index for the high bran recipe was closer to the theoretical value obtained for closed cells (n = 2) [6]. The mechanical properties found for the refined wheat flour (RF) recipe which are closer to the ones of open-cell structures, appear in good agreement with the results reported by Babin et al. (2007) [3] but are contradicting the results of Trater et al. (2005) and Robin et al. (2010) [4, 7]. The later reported mechanical properties closer to those of closed-cell structures.

3.2. Effect of cellular structure on mechanical properties

3.2.1. At same concentration of wheat bran

As previously mentioned, the fitting of the experimental values with the Gibson-Ashby model was not satisfying. Within the sample population at a given product composition, discrepancies with the model could be observed (Fig. 1). Samples having a similar relative density D show different mechanical properties. For instance, both the refined wheat flour samples extruded at condition 5 (180 °C, 18 % water content in the feed and 400 rpm) and at condition 8 (120 °C, 22 % water content in the feed and 800 rpm) had a similar relative density (D = 0.043 vs. 0.041) (Table 1 and Fig. 1). However the stress at rupture of the sample extruded at condition 8 (RF8) was significantly higher (σ^* = 0.86 MPa vs. 0.32 MPa) (Table 1). This difference may be related to their difference in cellular structure. Indeed, the sample extruded at condition 8 (RF8) was characterized by a higher density of cells (N_c = 740 cm^{-3} vs. 320 cm^{-3}), slightly smaller cells (MCS = 1940 μm vs. 2180 μm) and a lower mean cell wall thickness (MCWT = 30 μm vs. 45 μm) (see Table 1). These results suggest that, irrespective of the bran concentration, finer structures with a higher number of small cells required more strength to be ruptured. This was in good agreement with previous reported studies [3, 4]. As these samples were extruded under different conditions, differences in cell wall properties may also contribute to these differences.

3.3.2. At different wheat bran concentrations

At similar relative density, increasing the bran concentration to the low level (LB) led to higher stress at rupture and elastic modulus (see Fig. 1). Observation was made when comparing the refined flour sample extruded at condition 1 (RF1, 120 °C, 18 % water content in the feed and 400 rpm) with the low bran sample extruded at conditions 8 (LB8, 180 °C, 22 % water content in the feed and 800 rpm), these two samples having a similar relative density (D = 0.065 vs. 0.066). The low bran sample extruded at condition 8 (LB8) showed a significant higher stress at rupture than the refined wheat flour sample extruded at condition 1 (RF1) (σ^* = 1.15 MPa vs. 0.58 MPa) (see Table 1). The low bran sample (LB8) was characterized by a finer structure with a higher cell density (N_c = 2120 cm^{-3} vs. 100 cm^{-3}), a lower mean cell size (MCS = 410 μm vs. 1610 μm) and a lower mean cell wall thickness (MCWT = 25 μm vs. 70 μm) than the one of the refined flour sample (RF1) (Table 1). This is therefore consistent with the fact that finer structures would lead to foams with a higher strength, as previously reported within samples of same composition.

Further increasing the bran concentration to the high level (HB) shifted the power law index of the Gibson-Ashby model towards higher values (Fig. 1). The difference in stress at rupture between the low bran (LB) and the high bran (HB) recipes appeared to depend on the samples relative density. At high relative density, the low bran (LB) and high bran (HB) samples extruded at condition 3 (LB3 and HB3, 120 °C, 22 % water content in the feed and 400 rpm) exhibited similar relative density (D = 0.183 and 0.202) (see Table 1). The stress at rupture was higher for the high bran sample (HB3) than for the low bran (LB3) sample (σ^* = 2.93 MPa vs. 1.80 MPa) (see Table 1). The higher stress at rupture measured for the high bran sample (HB3) was associated to a finer structure with a higher density (N_c = 170 cm^{-3} vs 120 cm^{-3}) of smaller cells (MCS = 580 μm vs. 820 μm) and lower mean cell wall thicknesses (MCWT = 90 μm vs. 110 μm) compared to sample LB3 (see Table 1). This is therefore consistent with the fact that finer structures would lead to foams with a higher strength, as previously reported within samples of same composition. On the opposite, at low relative density the stress at rupture of the high bran sample extruded at condition 2 (HB2) was significantly lower than the one of the low bran sample extruded at condition 1 (LB1) (σ^* = 0.55 MPa vs. 0.87 MPa) (Fig. 1). Both had similar relative density (D = 0.089 vs. 0.084) but the sample HB2 had a finer structure (N_c = 3650 cm^{-3} vs. 510 cm^{-3} and MCS = 210 μm vs. 1140 μm) than LB1 (Table 1). According to the results earlier reported, this finer structure should lead to a higher strength of the extruded body.

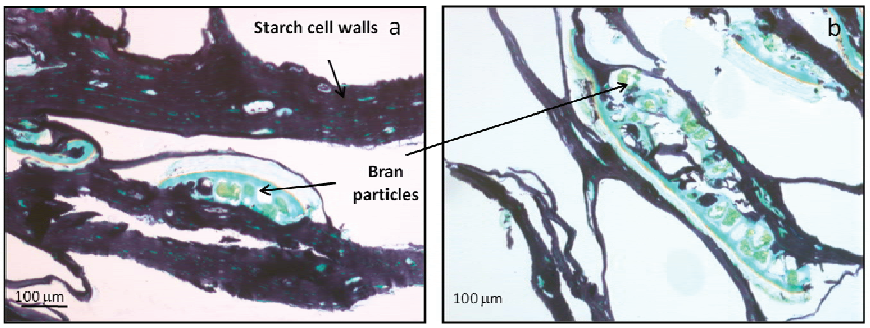

Fig. 2: Microscopy pictures of samples extruded at condition 2 with low bran concentration (a) and high bran concentration (proteins are stained in green, starch is strained in blue/purple)

An explanation may be the relationship between the dimensions of the bran particles and the cell wall dimensions. Both are modified depending on the extrusion conditions and bran concentration. As observed in the microscopy images of the foam cell walls extruded at different conditions shown in Fig. 2, the bran particles (stained in green) were surrounded by the starch continuous phase (stained in blue/purple). The cell wall thickness was affected by the process conditions. It increased linearly with the relative density, for all bran concentrations (correlation factor, r^2 = 0.92, 0.95 and 0.91 respectively for refined flour, low bran and high bran recipes) (Table 1). Therefore, decreasing the relative density always led to thinner cell walls. At constant bran size and aspect ratio of the bran particles, the presence of bran in thinner cell walls is more likely to affect the mechanical properties due to the low adhesion between bran and continuous starch matrix.

These observations may allow explaining the changes in mechanical behavior at varying bran concentration from the low bran concentration to the high one with the foam relative density. The samples, HB2 and LB1, generated at low relative densities (D ~ 0.065) had low mean cell wall thicknesses (MCWT = 30 μm and 25 μm) (Table 1). The samples, LB3 and HB3, obtained at higher relative density (D ~ 0.190) were characterized by a higher mean cell wall thickness (MCWT = 110 μm and 90 μm, respectively) (Table 1). For the sample LB1 and HB2 showing low mean cell wall thickness,

the ratio between the bran particle thickness and the mean cell wall thickness is higher than the one for LB3 and HB3. Thus, the effect of the bran on the cell walls mechanical properties may be more significant for samples LB1 and HB2 than for samples LB3 and HB3. As the bran fraction in the sample HB2 sample is higher than in sample LB1, the cell walls are weaker. Thus the sample HB2 exhibits a lower stress at rupture, despite its finer cellular structure. The samples LB3 and HB3 were characterized by higher cell wall thicknesses. Thus the effect of the bran particle on the cell walls was reduced. Therefore, the finer structure obtained when increasing the bran concentration was responsible for the higher stress at rupture obtained for sample HB3 compared to sample LB3.

4. Conclusion

At similar relative density (hence porosity), supplementation of extruded wheat flour with wheat bran led to cellular structures with a higher strength. This was attributed to the finer cellular structure with lower cell size and higher cell density obtained by extrusion of bran-containing starchy products. To improve the textural properties of products containing wheat bran, coarse cellular structures, closer to the ones obtained with the refined wheat flour, should be targeted. This may be obtained by optimizing the extruder parameters and the recipe composition.

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References

[1] Yanniotis S, Petraki A, Soumpasi E. Effect of pectin and wheat fibers on quality attributes of extruded cornstarch. *J Food Eng* 2007; **80**:594-599

[2] Brennan M, Monro JA, Brennan CS. Effect of inclusion of soluble and insoluble fibres into extruded breakfast cereal products made with reverse screw configuration. *Int J Food Sci Tech* 2008; **43**:2278-2288

[3] Babin P, Della Valle G, Dendeviel R, Lourdin R, Salvo L. X-ray tomography study of the cellular structure of extruded starches and its relations with expansion phenomenon and foam mechanical properties. *Carbohyd Polym* 2007; **68**:329-340

[4] Robin F, Engmann J, Pineau N, Chanvrier H, Bovet N, Della Valle G. Extrusion, structure and mechanical properties of complex starchy foams. *J Food Eng* 2010; **98**:19-27

[5] Hildebrand T, Rüegsegger P. A new method for the model-independent assessment of thickness in three-dimensional images. *J Microsc* 1997;**187** (1):67-75

[6] Gibson LJ, Ashby MF. *Cellular Foams: Structure and Properties*. 2nd ed. Cambridge: Cambridge University Press; 1997

[7] Trater AM, Alavi S, Rizvi SSH. Use of non-invasive X-ray microtomography for characterizing microstructure of extruded biopolymer foams. *Food Res Int* 2005; **38**:709-719

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